Kinetic simulation of heat pulse propagation through the tokamak scrape-off layer

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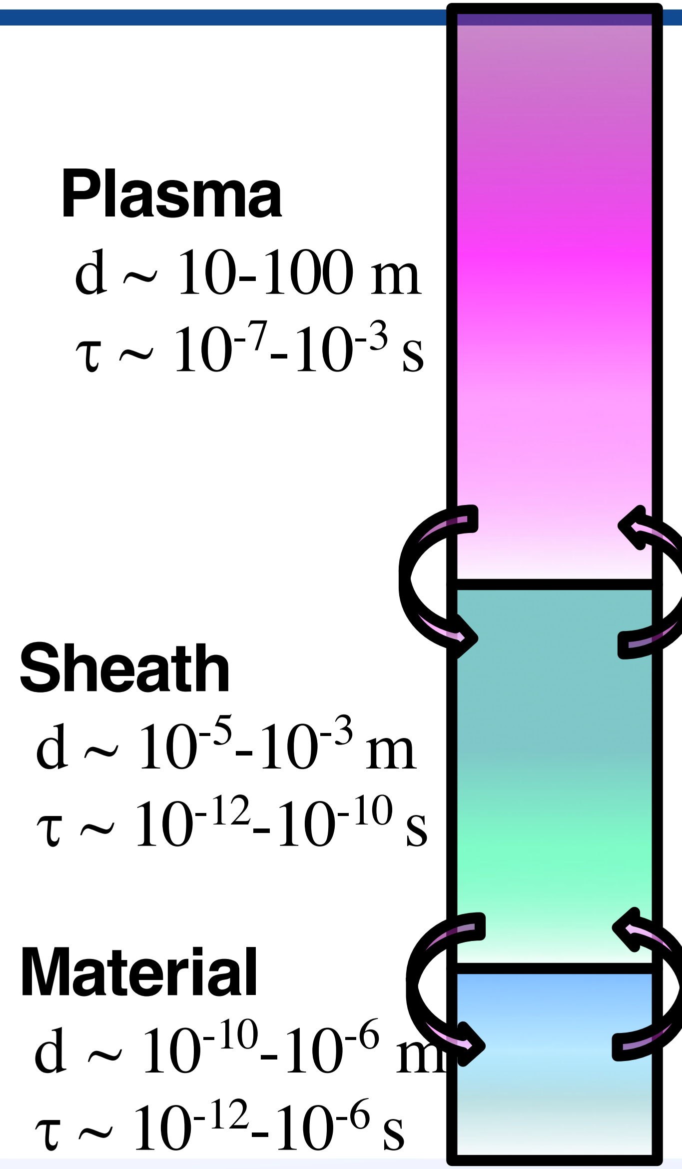
Motivation: Prediction of particle and heat fluxes in future magnetic fusion devices such as ITER

- **The PSI SciDAC is developing coupled models for the dynamic interaction between plasma & material surfaces at the edge of a magnetically confined fusion energy reactor**

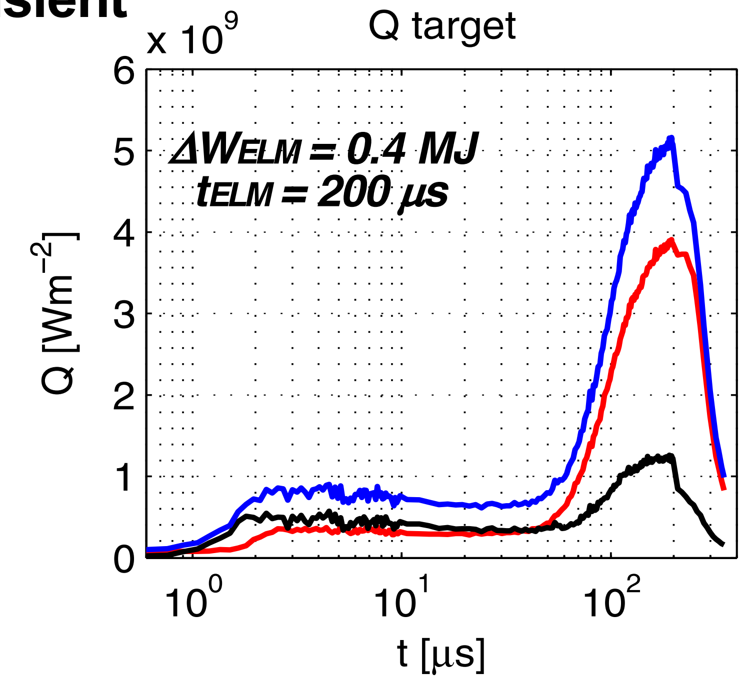
- **Our goals are to**
  - Determine importance of ELMs on impurity production & material erosion
  - Understand dynamic recycling during transient events



Goal: Simulate heat pulse propagation through the scrape-off layer (SOL) edge plasma

- **Goal: Determine the erosion rate of material surfaces that are impacted by large transient events such as edge localized modes (ELMs)**

- **Study the transient behavior of a heat pulse as it travels along a flux tube using the 4D drift-kinetic COGENT code**
  - Results will be benchmarked against heat pulse test problems that have been used to compare physics models and numerical algorithms



E. Havlikoca, Plasma Phys. Control. Fusion 54 (2012) 045002

- **An important goal will be to determine under what conditions energetic particle tails are found to form and whether kinetic effects impact quantitative results**

Plan: develop 4D COGENT model for ELM-relevant simulation of transient heat loads

- **Develop a 4D COGENT model for simulation of transient heat loads relevant to edge-localized mode instabilities (ELMs)**
  - Implement ELM-relevant heat pulse model within the COGENT code in simplified geometry & perform verification studies
  - Predict the plasma fluxes impinging on the sheath
  - Compare heat pulse simulations to fluid models and experimental data
  - Develop models for nonlinear sheath BCs & for accurately exchanging data with sheath code

- **As new capabilities are developed jointly with the ESL team & AToM-SciDAC, we will develop new capabilities**
  - Unlike species collisions: electron-ion
  - Neutral physics models including ionization, charge-exchange, radiation
  - Implicit treatment of both collisionless and collisional kinetic transport
  - 5D simulation of drift-kinetic plasma instabilities

Overview of COGENT

- **COGENT is a full-*F* continuum gyrokinetic (GK) code**
  - Multi-species gyro-kinetic equations and gyro-Poisson field equations
  - Fokker-Planck collision operators
  - At present, the code handles the long-wavelength drift-kinetic regime $k\rho<<1$, but extension to short wavelength is planned for the future
  - Reduced physics models are also available: model collision operators, vorticity equation, fluid electrons, etc.

- **To date, the main research thrust has been focused on obtaining axisymmetric solutions in realistic tokamak geometry, in isolation from wall physics**
  - A non-axisymmetric (5D) version of the code has recently become operational and has been successfully verified in the simulations of the collisionless drift (universal) instability in simplified slab geometry

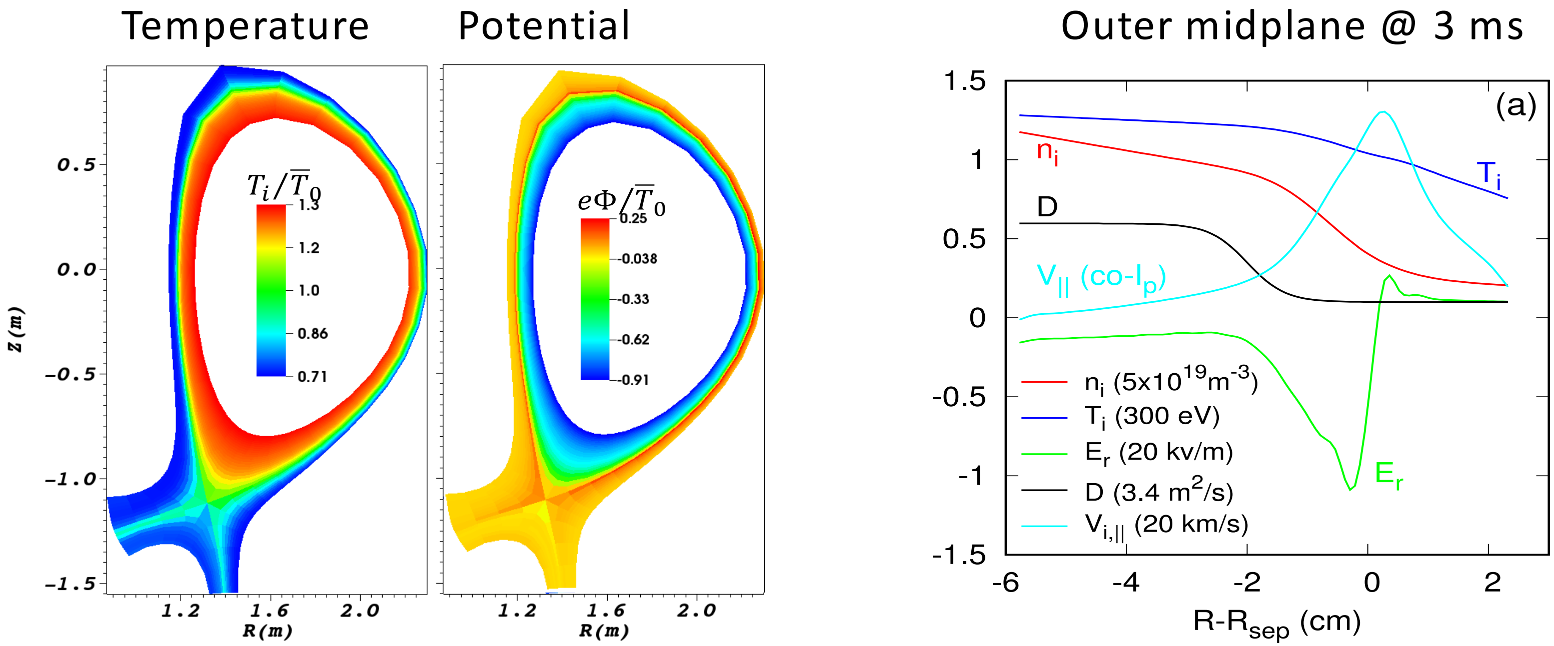
- **We will focus on improving the capabilities necessary for modeling plasma-wall interactions in the divertor region**

The COGENT team includes both physics & math developers

- **COGENT is part of the Edge Simulation Laboratory (ESL), the integrated modeling (AToM) SciDAC, and the PSI SciDAC**
  - **ESL:** FES physics team at LLNL & ASCR applied math team at LBNL & LLNL

- **Algorithmic Capabilities**
  - **4th Order Finite Volume Discretization and interpolation**
    - Discretization errors are bounded, even near the X-point of a separatrix
  - **Mapped multiblock grid technology**
    - Flux surfaces in different topological regions are mapped from the physical toroidal geometry onto topologically rectangular grid blocks
    - High-order interpolation is used to provide data communication in the region where grid blocks overlap, e.g. near the X-point
  - **Implicit algorithms & IMEX capability**
    - IMEX capability has been successfully used to treat the Fokker-Planck collision operator implicitly for like-species collisions
    - Improves simulation efficiency well into the collisional regime, a regime that is notoriously difficult to treat using kinetic codes

Example: COGENT has recently obtained self-consistent results for the tokamak pedestal*



- Results of an axisymmetric (4D) COGENT simulation of cross-separatrix plasma transport in a DIII-D discharge using full Fokker-Plank ion-ion collisions and self-consistent 2D electrostatic potential variations with the reduced vorticity model for isothermal electrons.

*M. Dorf and M. Dorr, Contrib. Plasma Phys. (2018) DOI: 10.1002/ctpp.201700137.

ELM Benchmark (*): determine heat flux due to ELMs for JET-like pedestal parameters

- **JET-like SOL parameters**
  - B_t = 3 T, R = 3 m, L_{pol} = 8.3 m
  - angle = 6°, B_p/B_t = 0.11
  - 2 L_{ll} = 80 m, L_{src} = 25 m

$m_i = 2\ m_p$

$n_{ped} = 5\text{x}10^{19}\ \text{m}^3$

T_{ped} = 1.5 keV

$C_{s,ped} = 3.8\text{x}10^5$ m/s

- **Maxwelian Source**
  - Source parameters are set to the pedestal parameters (A=1.2)

$$S = \frac{S_{src}}{\left(2\pi T_{src}^3\right)^{1/2}} e^{-\left(mv^2/2+\mu B\right)/T_{src}} \qquad S_{src} = An_{ped}\ C_{s,ped}/L_{src}$$

- **(*) References**

1. E. Havlickova, W. Fundamenski, D. Tskhakaya, et al., Plasma Phys. Control. Fusion 54, 045002 (2012).
2. A. Chankin and D. P. Coster, Contrib. Plasma Phys. 54, 493 (2014).
3. E. L. Shi, A. H. Hakim, and G. Hammett, Phys. Plasmas 22, 022504 (2015).
4. T. D. Rognlien, R. H. Cohen, D. D. Ryutov, et al., J. Nucl. Mater. 438, S418 (2013).

We can develop understanding using kinetic ions and an adiabatic electron model

- **Collisionless kinetic ion model**

- **Adiabatic = Boltzmann electron model (fixed T_e)**

$$e\varphi = e\varphi_{sheath} + T_e \log(n_i/n_0) \qquad e\varphi_{sheath} = \frac{1}{2}T_e \log\left(V_{i||}^2 m_e/2\pi T_e\right)$$

- **Heat flux at target plate (Assume $T_e = T_i$ at target plate)**

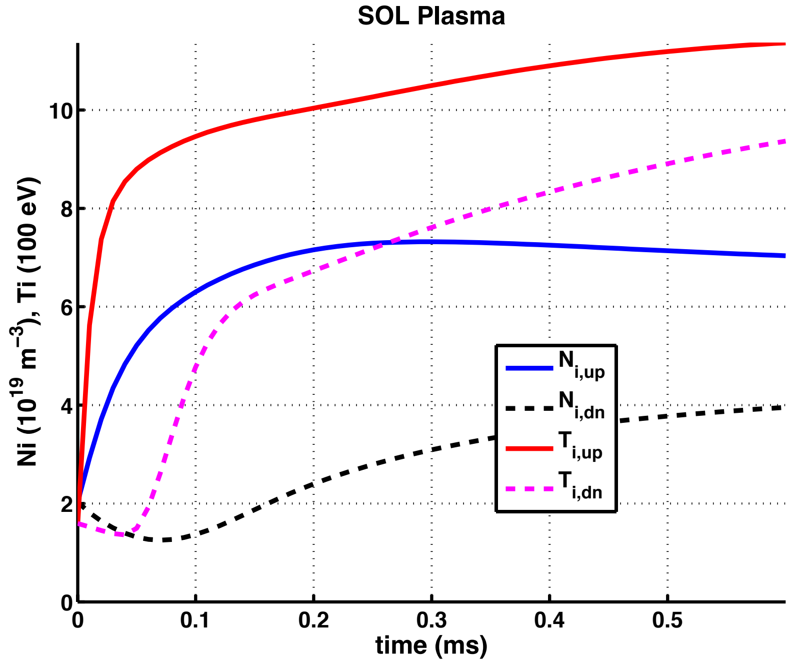
$$Q_i = Q_{i,conv} + Q_{i,cond} + Q_{i,sheath} \qquad Q_{tot} = Q_i + Q_e$$

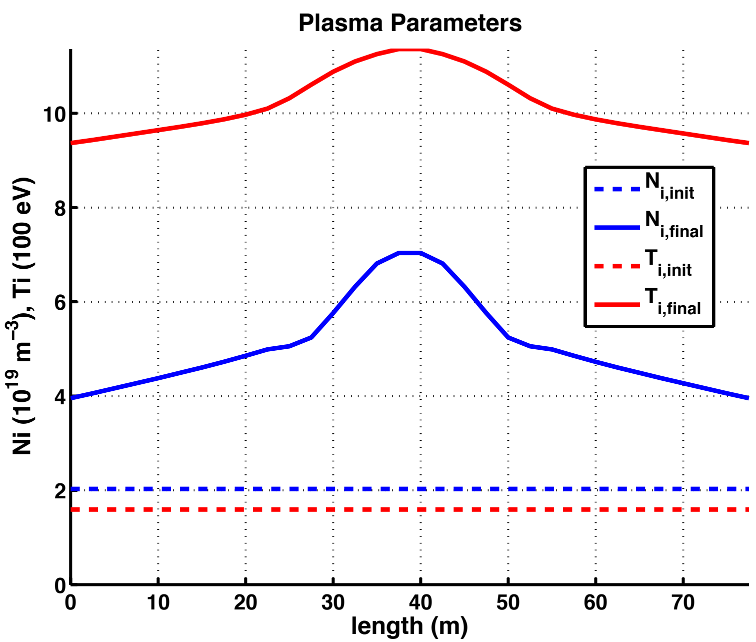
$$Q_{i,conv} = \frac{3}{2}T_i\Gamma_i \qquad Q_e = 2T_e\Gamma_i$$

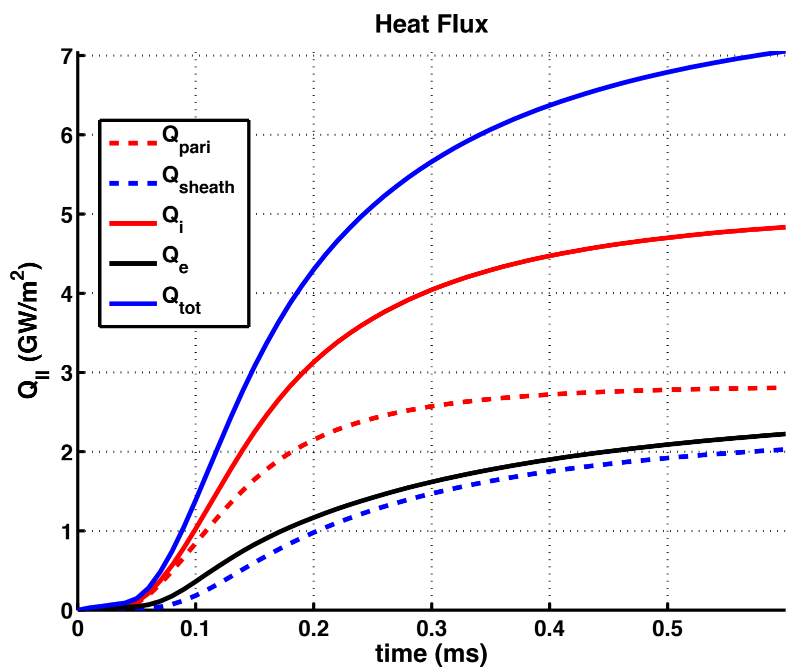
$$Q_{i,sheath} = e\varphi_{sheath}\Gamma_i$$

COGENT results: The heat is on!

- **Parameters for these cases**
  - Resolution: RxZ=8x32, $v_{\parallel}$ x μ = 32x32
  - $n_{SOL} = 2x10^{19}\ m^3$
  - T_{SOL} = 175 eV, T_e=210 eV
  - T_{src} = 1500 eV
  - $S_{src} = 9x10^{23}\ /sm^3$

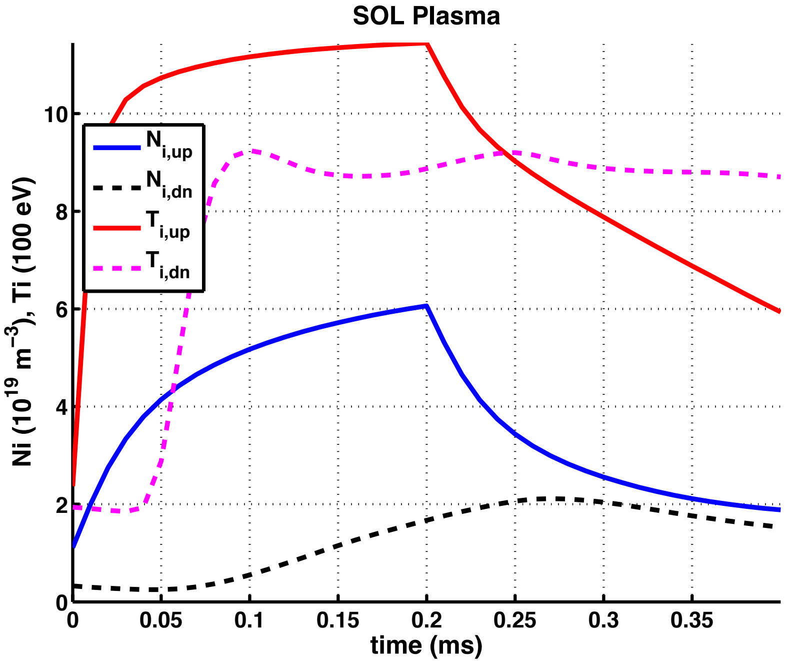


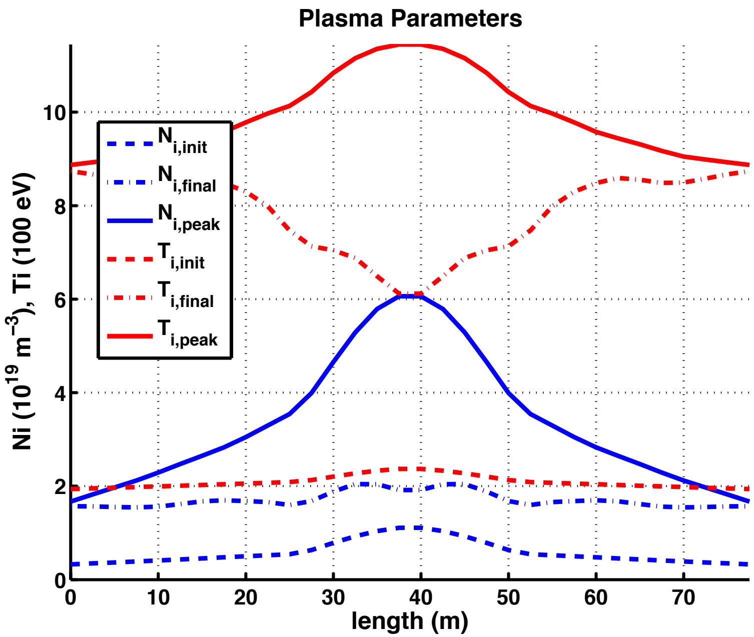


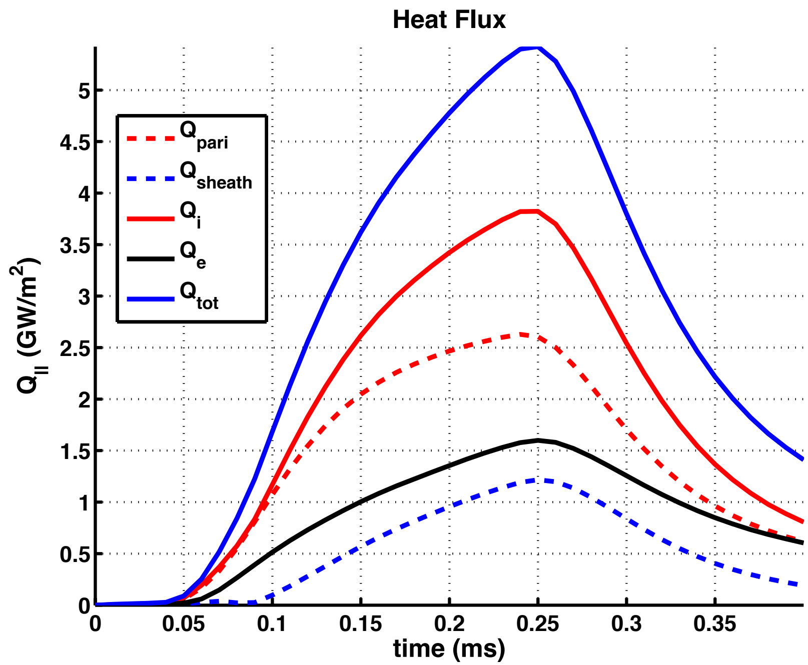


COGENT results: τ_{ELM} = 200μs Moments

- T_{up} rises to 1 keV
- T_{dn} rises to 0.9 keV
- Heat flux $Q_{||}$=5 HW/m² peaks after τ_{ELM}
- Temperature profile inverts after τ_{ELM}



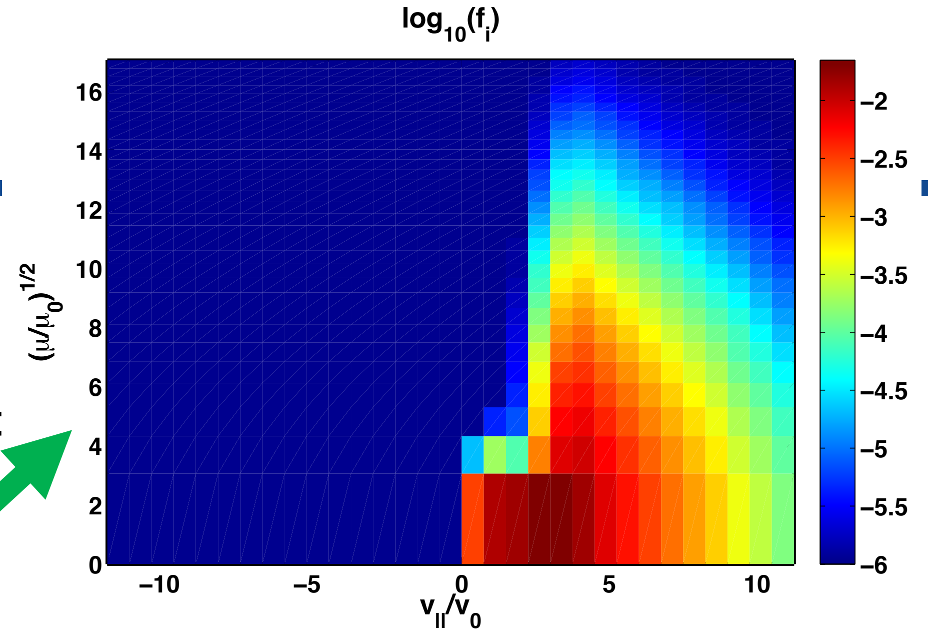


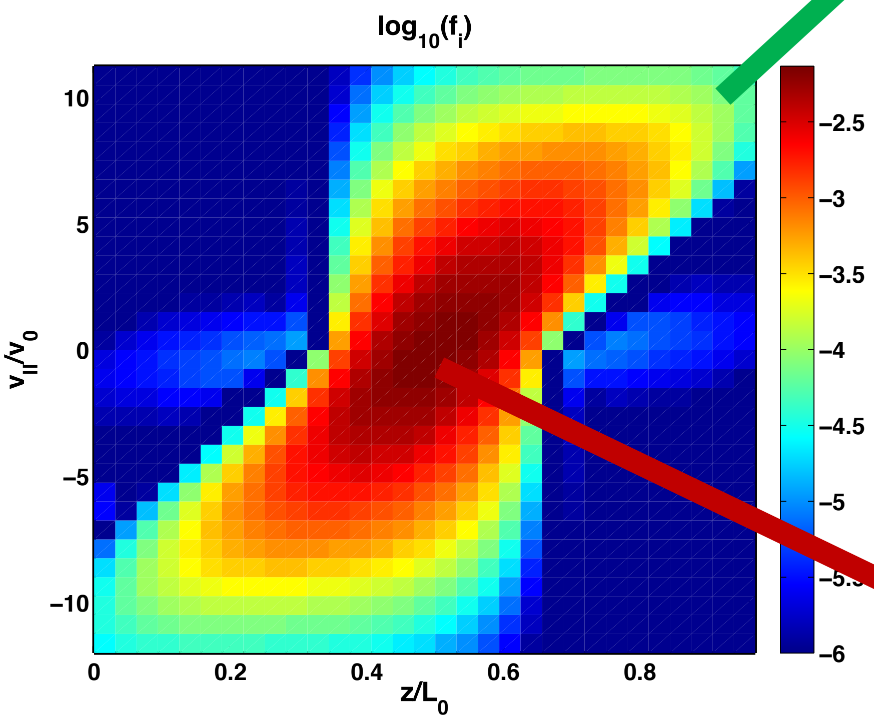


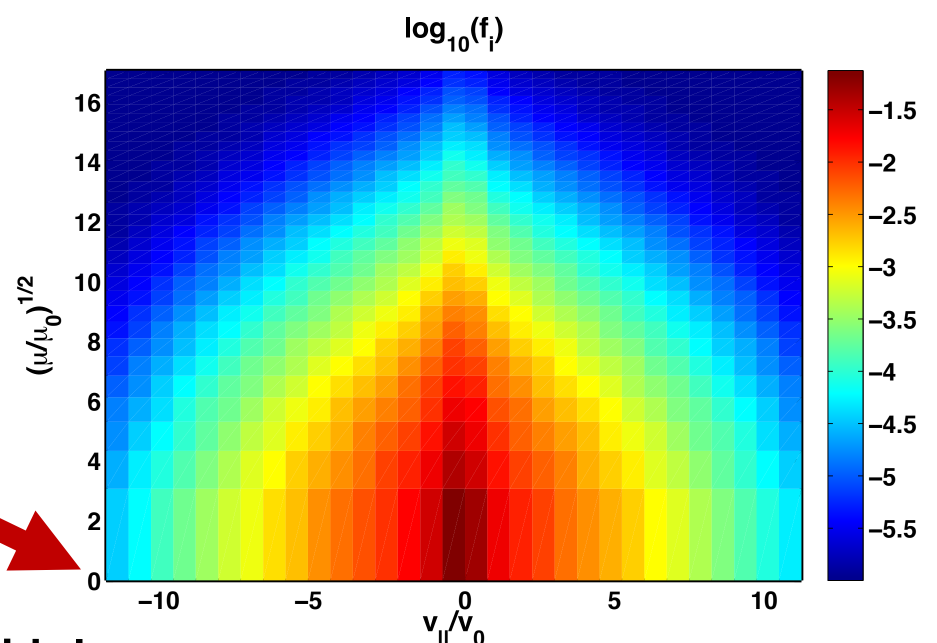
COGENT results: τ_{ELM} = 200μs
Particle distribution function

- **PDF is not Maxwellian**
  - Sonic outflows at target plates
  - $T_{\parallel} < T_{perp}$=1.5keV at midplane
  - Transition to ½ Maxwellian in $v_{\parallel}$ near target plates

Target plate

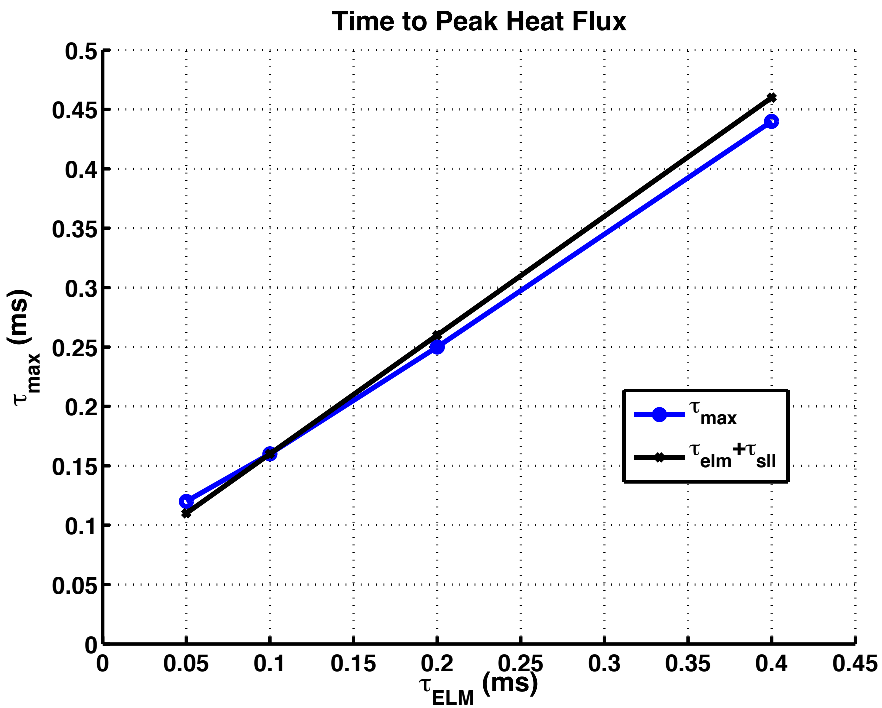


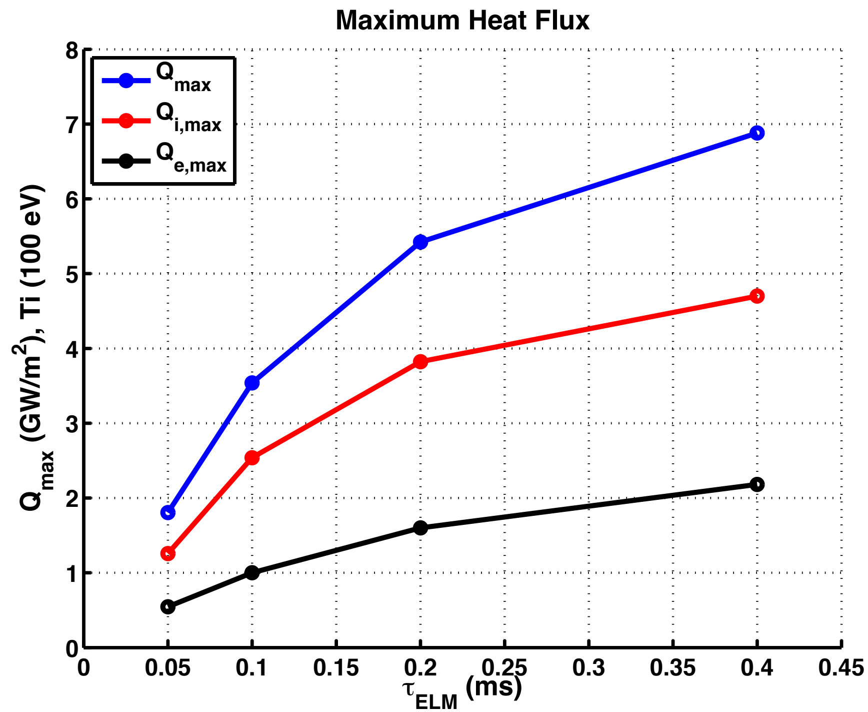




Midplane

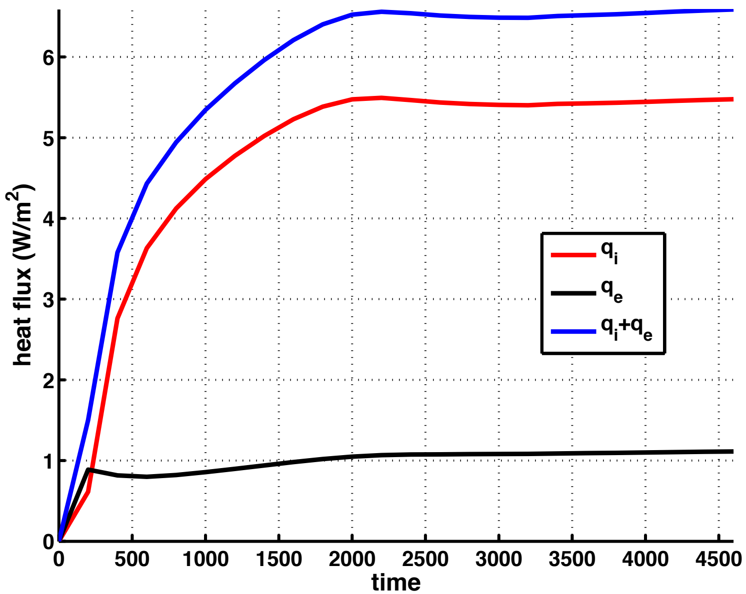
Dependence of maximum heat flux on τ_{ELM} is sublinear

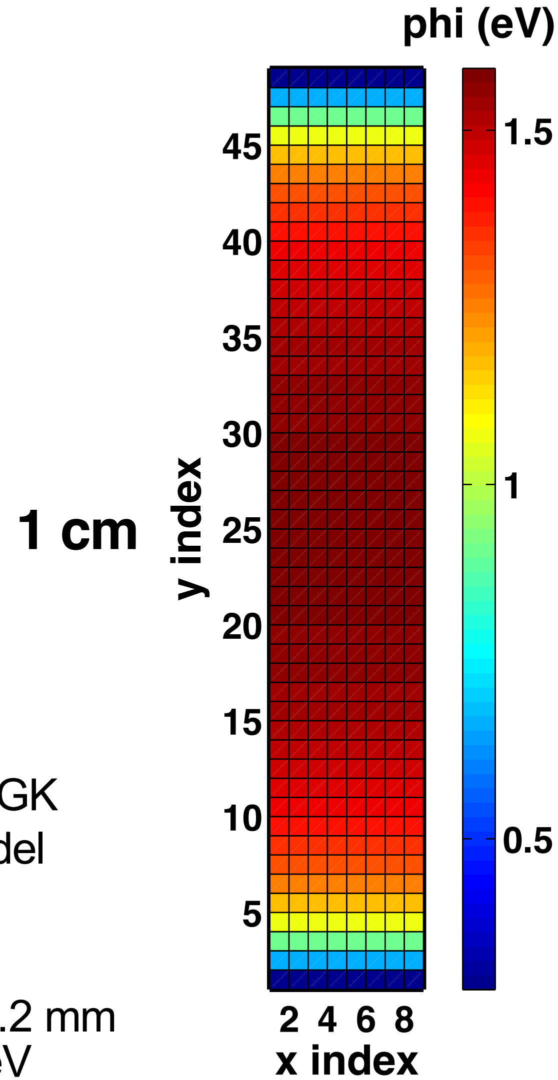




- **Maximum heat flux achieved ~ $\tau_{||}$ = 60 μs after τ_{ELM}**
- **Magnitude of heat flux $Q_{||}$ has a power law dependence on τ_{ELM} with exponent < 1**

We are working towards simulations with 2 kinetic species: electrons and ions





- **Example: Solution with a self-consistent sheath**

- Results of a simulation of the sheath using kinetic electrons with BGK collisions, kinetic hydrogen and a full 2D electrostatic potential model
  - Resolution: 8X x 48Y x 32V|| x 24μ

- Low density $n_e \sim 2 \times 10^{16}/m^3$ allows one to resolve the sheath $\lambda_d = 0.2$ mm in a domain of 1 cm length for temperature $T_e \sim 13.5$ eV, $T_i = 4.5$ eV

Implementation of "gyrokinetic sheath" BCs* allows for efficient quasineutral simulation of a large domain

- **Gyrokinetic Poisson: retain polarization current but eliminate vacuum polarization**
- **"Sheath BC" = electrons reflected if $m_e v_{||}^2/2 < \phi$ in last grid cell in domain before boundary**
- **Parameters:**

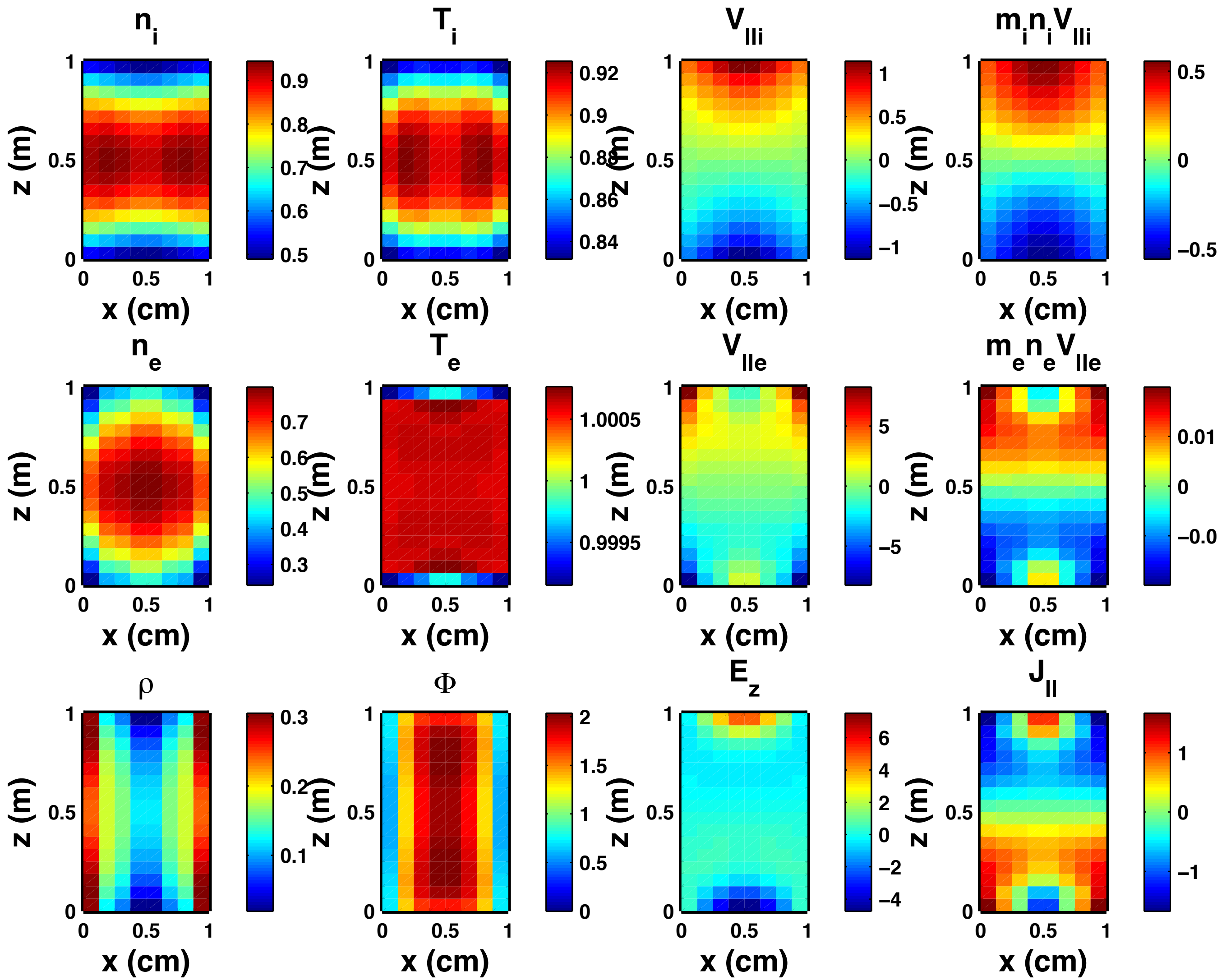
  $8R \times 16Z \times 32v_{||} \times 24\mu$

  $n_{init} = 10^{19}\ m^{-3}$

  $T_{init} = 100$ eV

  $m_e/m_i = 0.01$

  Snapshot at $t = 3\ \mu s$



*P. Collela, M. R. Dorr, D. D. Wake, J. Comp. Phys. 149, 168 (1999)

E. L. Shi, Ph.D. Dissertation, Princeton University (2017)

Future Work: explore the importance of kinetic plasma effects

- **Kinetic effects have the potential to strongly impact surface evolution**
  - **Heat fluxes are strongly flux-limited during the early phase of an ELM**
  - **Energetic ions can alter the**
    - ion saturation current
    - charge exchange rate
    - rates for implantation, sputtering, and defect formation
  - **Energetic electrons can alter the**
    - heat flux directed on PFCs
    - sheath potential which determines ion energy on impact
    - rates for threshold processes such as ionization, recombination, and radiation
  - **It is known that kinetic effects alters the quantitative ratio of electron to ion heat flux 1:1 vs. 3:1 (Havlikova PPCF 2012)**

- **Kinetic processes are potentially important for interpretation of experimental data and for validation exercises**
  - Non-Maxwellian distributions can change the interpretation of standard diagnostic techniques based on Langmuir probes and impurity radiation

Conclusions

- **PSI SciDAC is developing dynamically coupled plasma-wall models**
  - Ultimate goal is to determine the erosion rate of material surfaces that are impacted by large transient events such as ELMs
- **ELM heat pulse benchmark has been simulated using an adiabatic Boltzmann electron model**
  - Results appear to match reasonably well
  - Still need to perform numerical convergence study
- **Future work will focus on two kinetic species: both electrons and ions**